IDEA Dual-Readout Calorimeter – TB Analysis and Simulation

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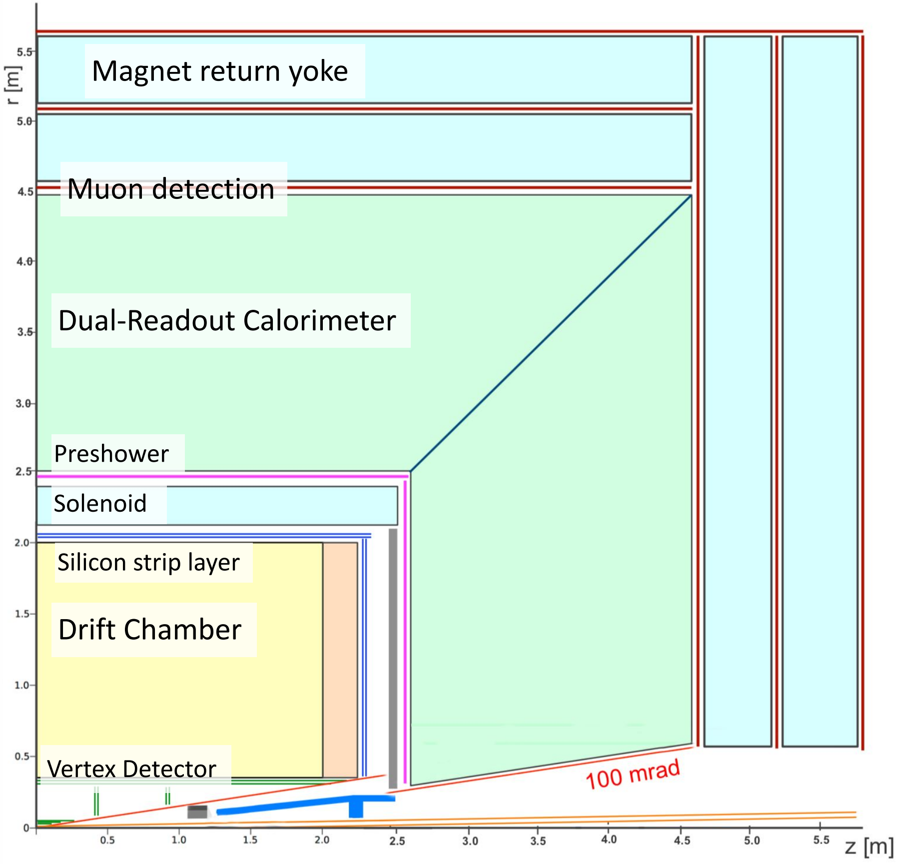
On behalf of the IDEA Dual-Readout Calorimeter Group

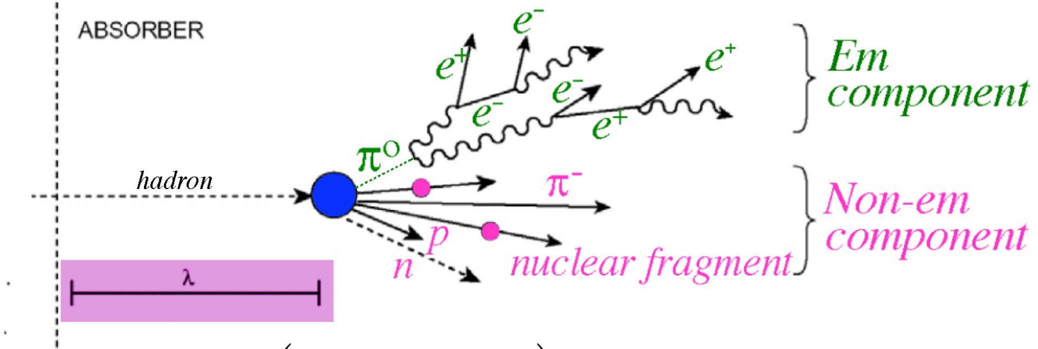
IDEA (Innovative Detector for Electron-positron Accelerators) [resource]

- Detector concept for future circular leptonic collider
- Key components:
  - **Vertex detector**: silicon pixels based on MAPS
  - low material **Drift Chamber**
  - **Silicon micro-strip layer**
  - Thin **Solenoid**: 0.7 X_0 and 0.16 λ_{int}, 2 T
  - **Preshower**: μ-RWELL placed behind absorber (barrel: Solenoid, forward region: **Lead plate**)
  - Single **Dual-Readout Calorimeter**: for both **EM** and **HAD** calorimetry
    - Option to have crystal ECAL being explored
  - **Muon detection**: μ-RWELL in 3 layers
  - **Magnet return yoke**



Dual-Readout Calorimetry [resource]

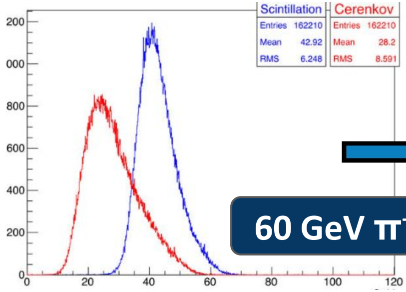
- Large fluctuations in fraction of **EM component** (f_{EM}) for hadronic showers
- If calorimeter response to **EM part** different from that to **non-EM part** (h/e ≠1): Energy resolution of calorimeter **largely limited by f_{EM}**
- Dual-Readout calorimetry allows to correct for fluctuations by **measuring f_{EM} event-by-event** using **two readout channels with different h/e**
  - **Scintillation** and **Cherenkov** channel
- Combining information from two readout channels **boosts energy resolution**



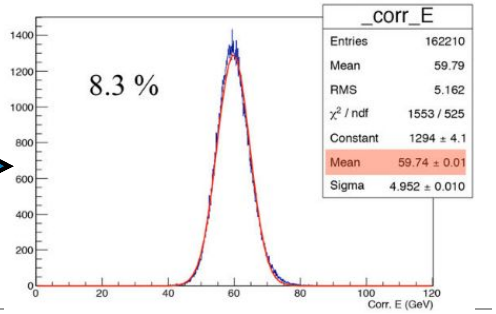
$$E_C = E\left(f_{em} + \left(\frac{h}{e}\right)_C (1 - f_{em})\right)$$

$$E_S = E\left(f_{em} + \left(\frac{h}{e}\right)_S (1 - f_{em})\right)$$

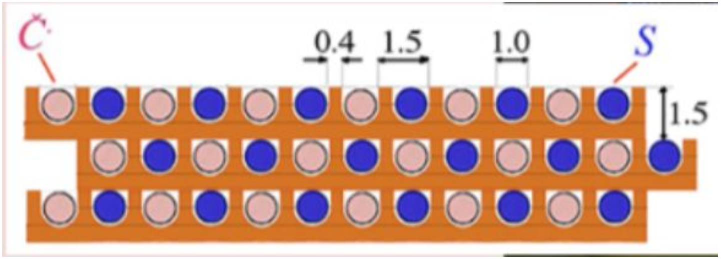
$$E = \frac{(E_S - \chi E_C)}{1 - \chi}$$

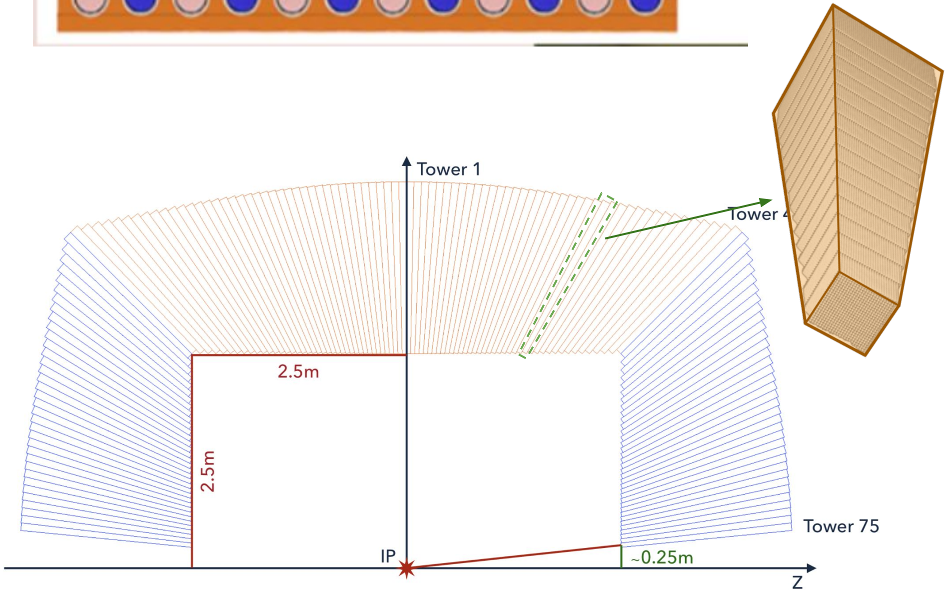


60 GeV π-



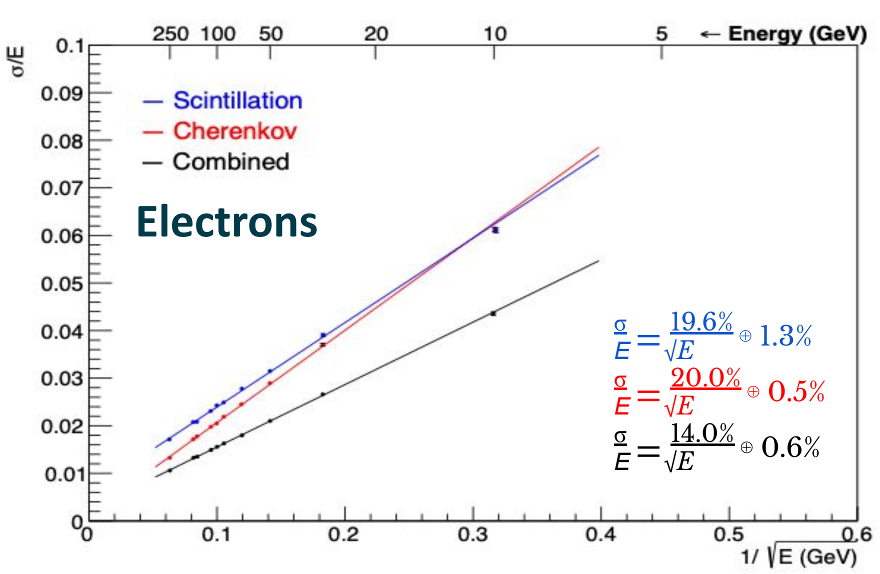
IDEA Dual-Readout Calorimeter [resource]

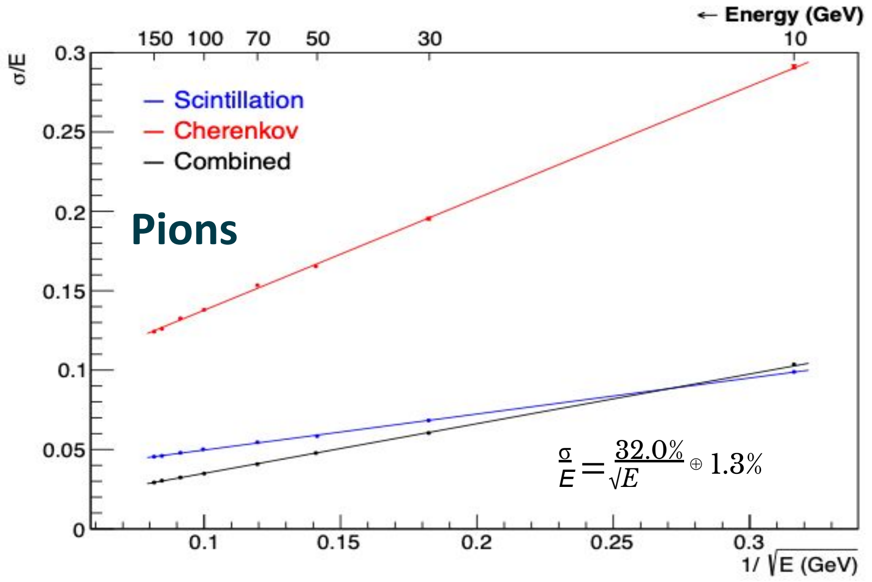




- **Copper** absorber
- 130 M fibres embedded in absorber in longitudinal direction:
  - 1 mm fibres, 1.5 mm pitch
  - Chess board layout of **Cherenkov** and **scintillation** fibres
  - Readout in the rear end by SiPMs
- High transverse granularity:
  - Excellent angular resolution
  - Lateral shower shape sensitivity
- Calorimeter depth of 2 m (~8 λ_{int})
- No longitudinal segmentation (out of the box)
- Full simulation including drift chamber and solenoid available: https://github.com/HEP-FCC/IDEADetectorSIM

Energy Resolution Performance in Simulation [resource]





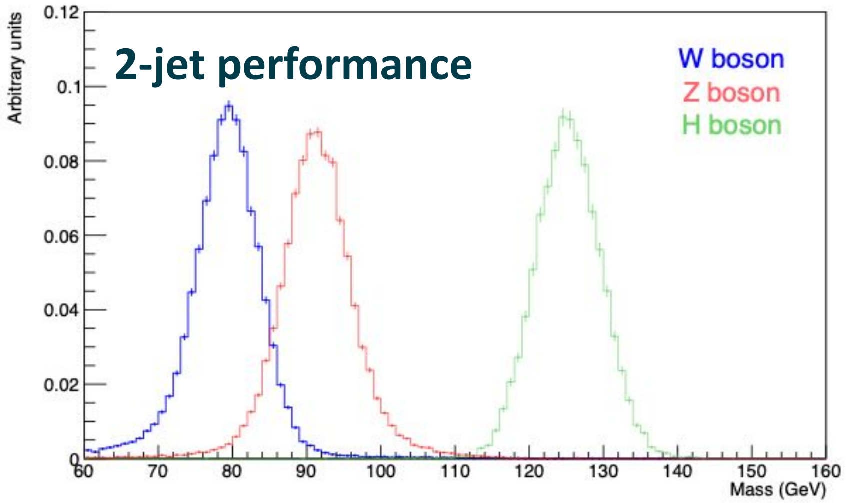
Electromagnetic Performance:

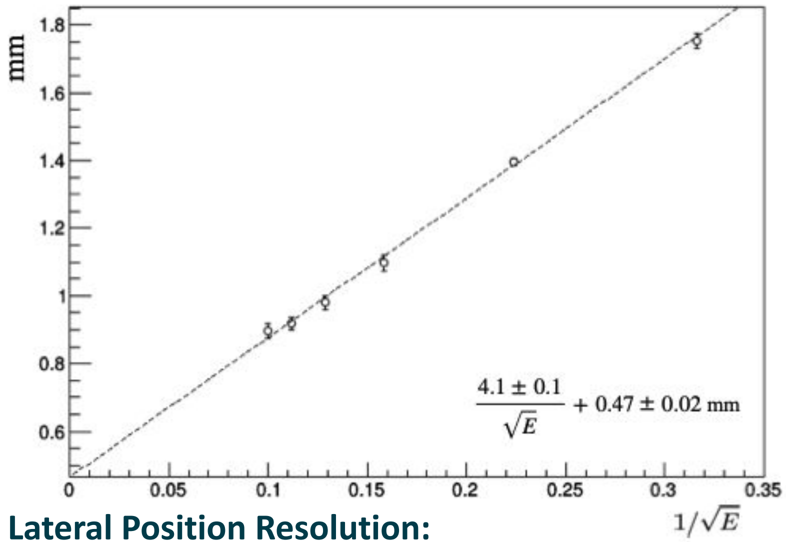
- $E = \dfrac{E_s/\sigma_s^2 + E_c/\sigma_c^2}{1/\sigma_s^2 + 1/\sigma_c^2}$
- linearity within ± 1% in energy range 10-250 GeV

Hadronic Performance:

- χ = 0.41 (value from Geant4 that correctly reconstructs primary particle energy)
- linearity within ± 1% in energy range 10-150 GeV

Energy Resolution Performance in Simulation [resource]





Jet Performance:

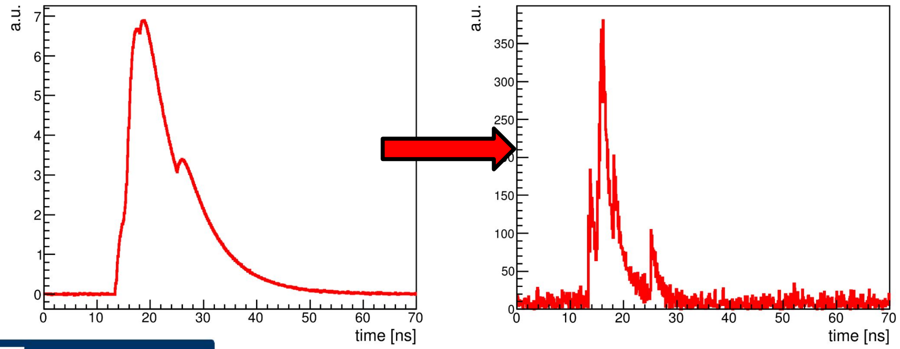
- back-to-back jets with energy ~ $E_{CM}/2$
- $\frac{\sigma}{E} = \frac{38\%}{\sqrt{E}}$
- Higgs: excluding *b* semileptonic decays

Lateral Position Resolution:

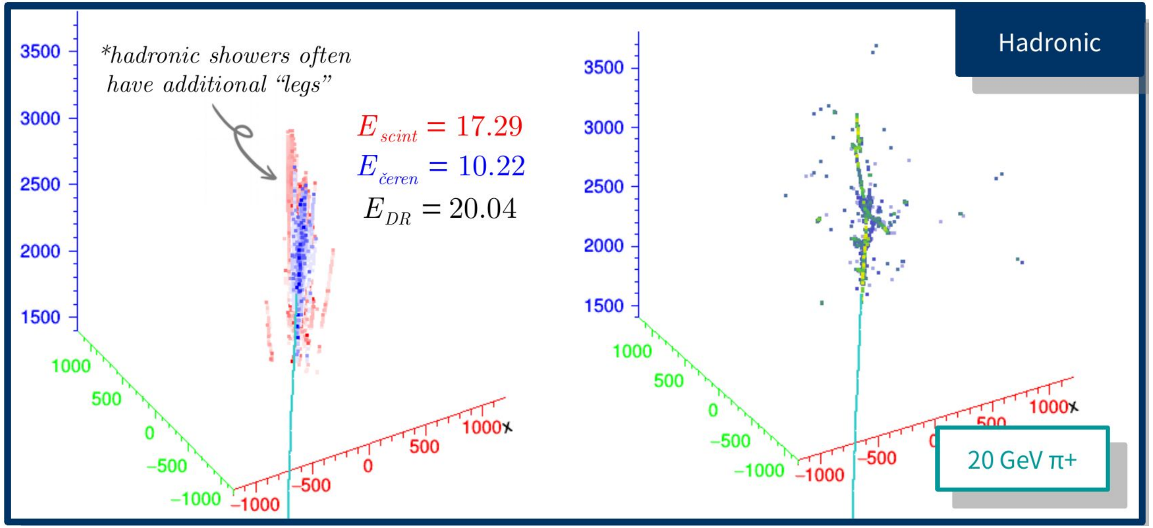
- Electron beams of varying energy shot at tower centre
- Gradually moved towards neighbouring tower
- Position of electrons calculated via centre of gravity method

Longitudinal Shower Shape through Timing [resource]

- For fibre-sampling calorimeters, need to rely on **timing information** for longitudinal segmentation
- Exponentially decaying photon signal for SiPMs
  - Fourier transf. to **extract individual contributions** to pulse



waveform created with SimSiPM



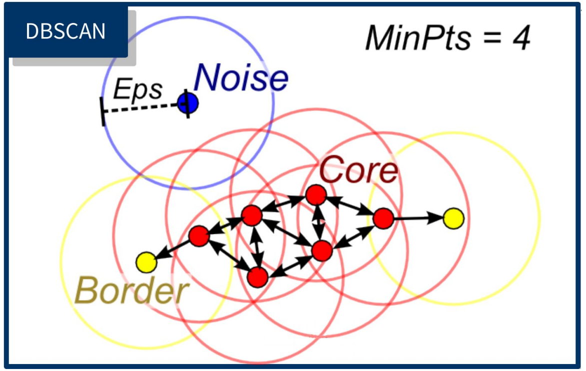
- Combining lateral granularity and longitudinal information allows **3D reconstruction** of shower shape
- Unlocks potential as **particle flow calorimeter**

Density-Based Clustering [resource]

- DBSCAN algorithm for clustering in 3D
  - does not require # of clusters a priori
  - suitable for arbitrary-shaped clusters
  - able to add weight to each point

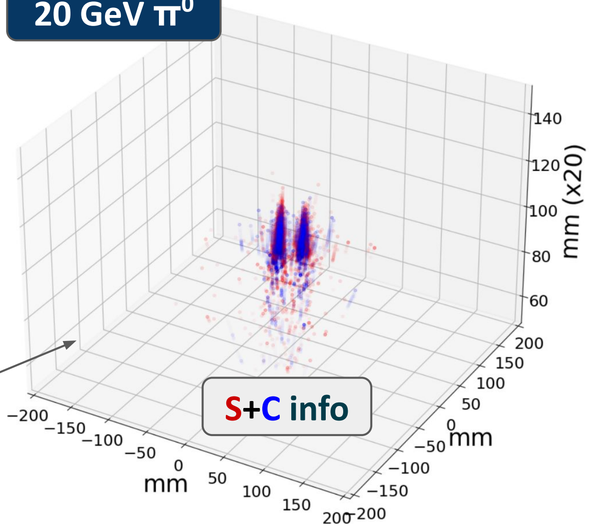
- DBSCAN does not consider different lateral (1.5 mm) & longitudinal (100 ps ≈ 4 cm) accuracy
  - need to scale longitudinal direction by factor of 20

DBSCAN

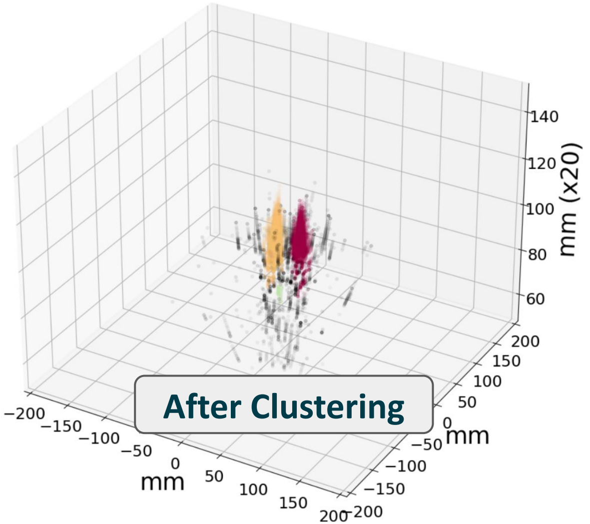


π^0 needs tighter ε with respect to other particle showers

20 GeV π^0



S+C info



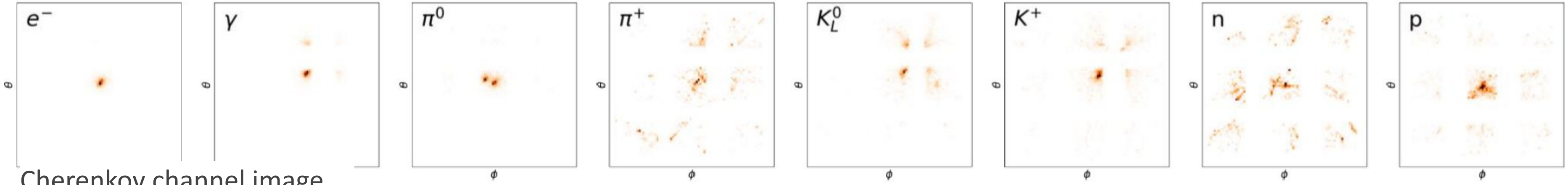
After Clustering

PID using Machine Learning [resource]

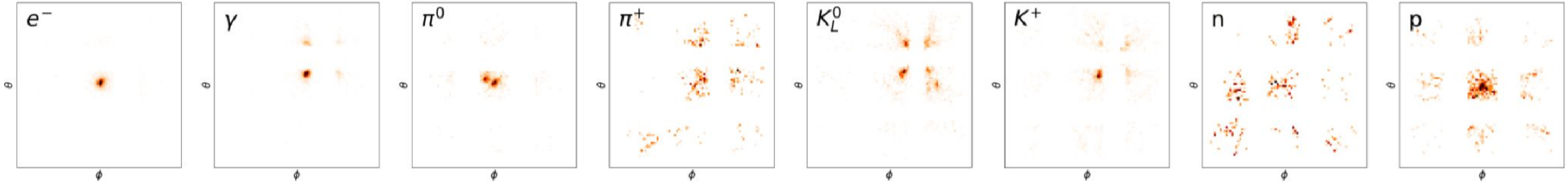
see also study with VGG and Residual NN

dark spots are more energetic

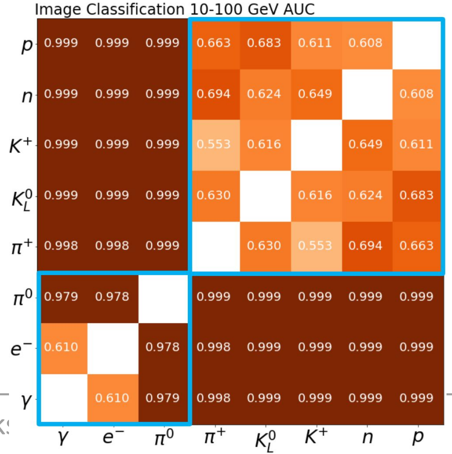
Scintillation channel image

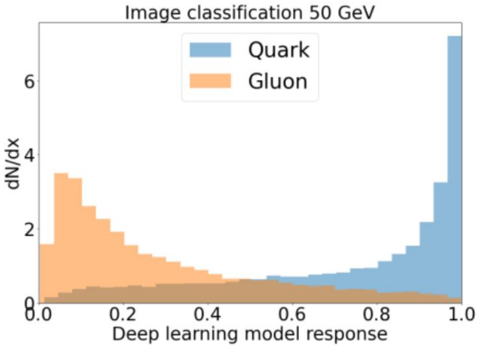


Cherenkov channel image



- Reconstructed shower images as input for Convolutional neural network (CNN)
  - Binary classification between two particles
- Strong π^0 vs γ/e separation
- Gluon jet vs. Quark jet separation ~80% efficiency (50-70 GeV)





τ-Decay Identification using ML [resource]

- Classification of τ decays and separation from QCD jets based on Dynamic Graph Neural Networks (DGCNN)
- **Image-based**: Treating the energy deposition on each fiber as the pixel intensity creates an image of the event
  - can use very advanced CNN for image identification
  - but unclear how to incorporate additional fibre informati (#photo-electrons, fibre-type, timing)
- **Point-cloud-based**: Unordered sets of entities distributed irregularly in space, analogous to the point cloud representation of 3D shapes
  - easy to incorporate additional information of the fibers
  - architecture of the neural network has to be carefully designed to fully exploit the potential of this representation → Dynamic Graph CNN

Decay	Label 8-class
$\tau^- \to e^- \nu_e \nu_\tau$	0
$\tau^- \to \pi^- \nu_\tau$	1
$\tau^- \to \pi^0 \pi^- \nu_\tau$	2
$\tau^- \to \pi^0 \pi^0 \pi^- \nu_\tau$	3
$\tau^- \to \pi^- \pi^- \pi^+ \nu_\tau$	4
$\tau^- \to \pi^0 \pi^- \pi^- \pi^+ \nu_\tau$	5
$\tau^- \to \mu^- \nu_\mu \nu_\tau$	6
$Z \to q\bar{q} \to jet\, jet$	7

Results using full SiPM emulation (Integral and Peak of signal, ToA, ToT, ToP) show no significant improvement

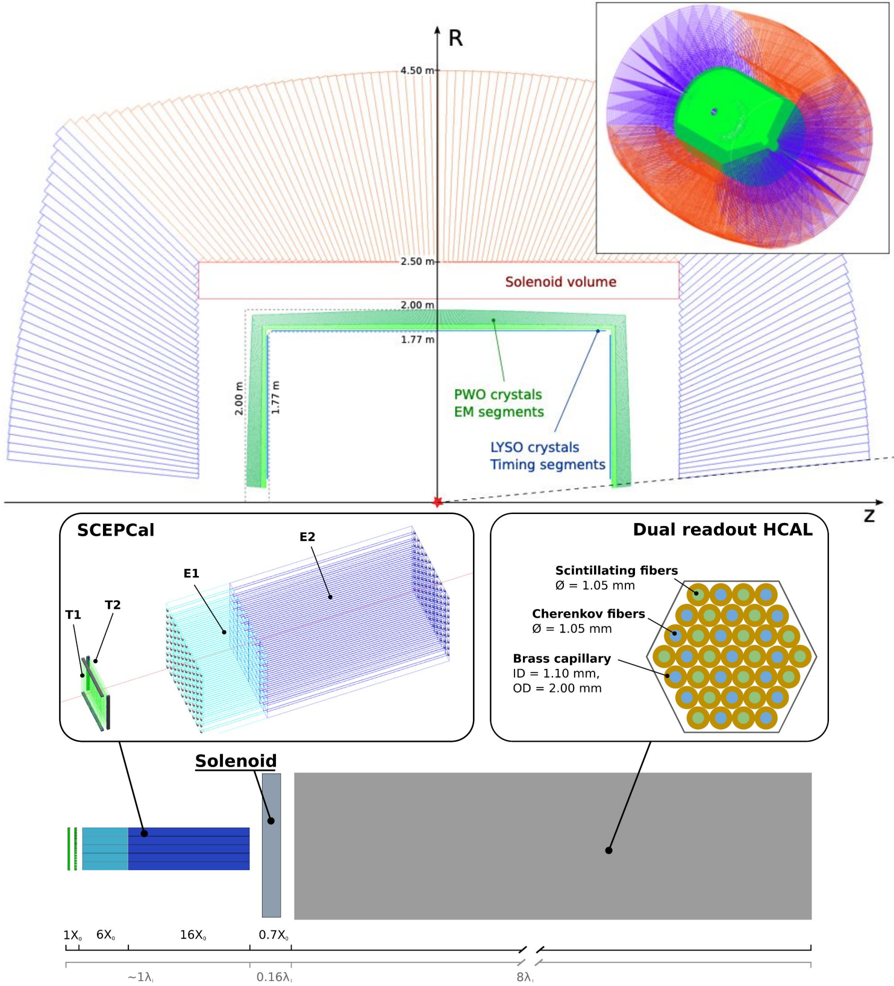
Using coordinates, fiber type (S/C) and p.e. in each fiber

Truth BR \ Predicted BR	τ →eνν	τ →πν	τ →ππ⁰ν	τ →ππ⁰π⁰ν	τ →πππν	τ →ππππ⁰ν	τ → μνν	Z →qq jets
τ →eνν	98.53	0.45	0.65	0.03	0.00	0.00	0.34	0.00
τ →πν	3.20	91.35	2.21	0.25	1.71	0.19	0.94	0
τ →ππ⁰ν	1.34	3.49	86.87	4.97	1.12	1.67	0.11	0.44
τ →ππ⁰π⁰ν	0.46	0.25	12.09	83.19	0.14	3.24	0.00	0.63
τ →πππν	0.11	3.14	1.24	0.16	87.39	6.79	0.00	1.16
τ →ππππ⁰ν	0.16	0.30	1.82	1.57	6.42	87.04	0.03	2.66
τ → μνν	1.24	0.25	0.06	0.00	0.03	0.00	98.42	0.00
Z →qq jets	0.13	0.21	0.21	0.59	1.87	2.29	0.03	94.67

Avg. accuracy: 90.8%

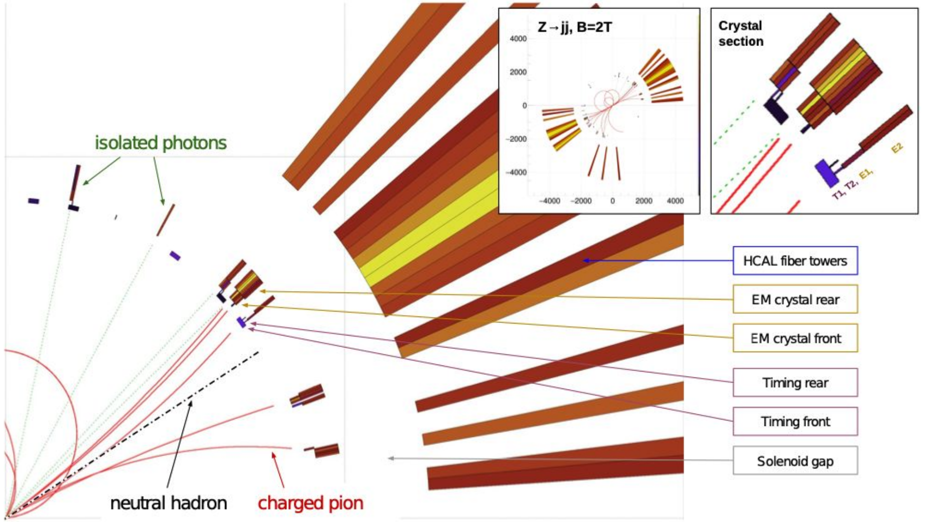
Crystal Calorimeter [resource]

- Alternative design with **crystal, dual-readout ECAL** under investigation
- Combine Dual-Readout (DR) technique with coarsely long. segmented crystal calo in front of solenoid
  - Improves EM energy resolution
  - Longitudinal segmentation allows for (simple) particle flow algorithm
- two thin **LYSO layers** for timing (1 X_0 - time res. 20 ps)
  - rotated by 90° wrt each other to create 3x3 mm^2 grid
- two **PWO crystal layers** (22 X_0 ; 0.97 λ_I):
  - 1x1 cm^2 cross section
  - 1 SiPM for front layer
  - 2 SiPM for back layer -> DR for hadrons that start showering in crystals by exploiting wavelength spectrum differences between S and C

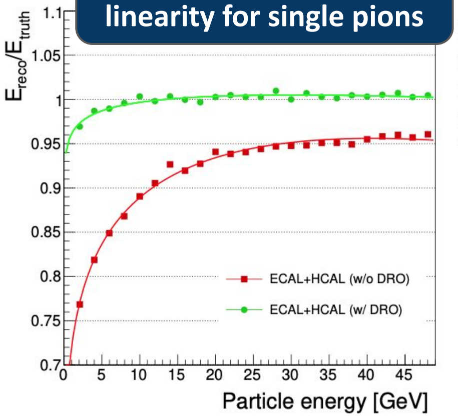


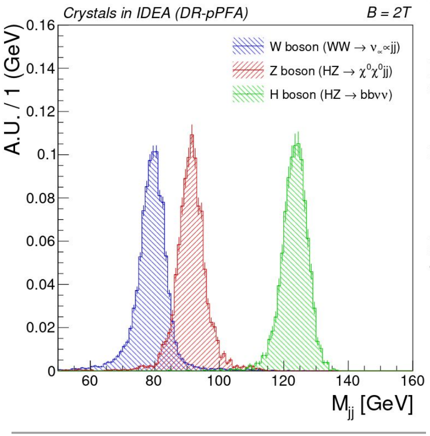
Crystal Calorimeter [resource]

- Longitudinal segmentation into ECAL and HCAL simplifies particle flow approach
  - matching of tracks with calo clusters based on expected energy deposit
- Combining Dual-Readout with particle flow shows good improvement in energy linearity and resolution

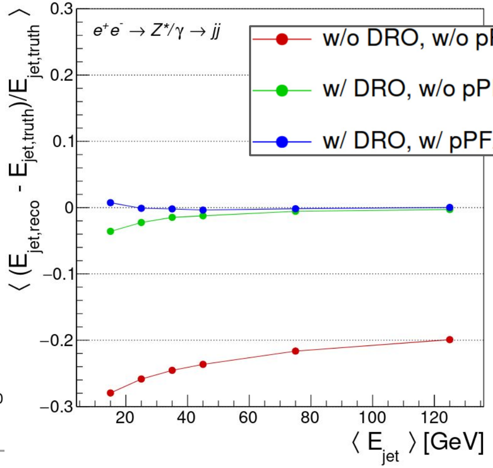


Effect of DR on energy linearity for single pions

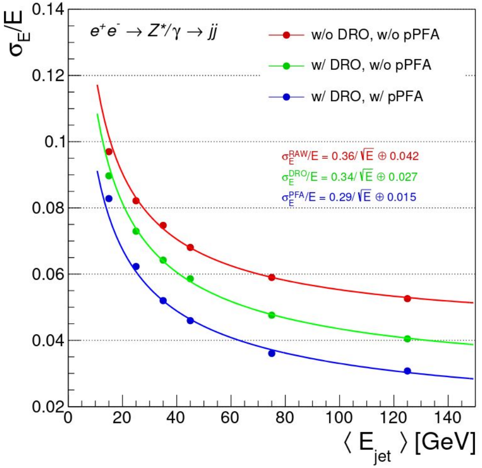




Jet energy scale



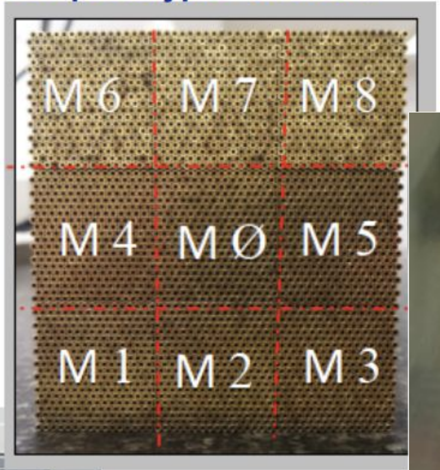
Jet energy resolution



2021 Testbeam (Bucatini Prototype) [resource1] [resource2]

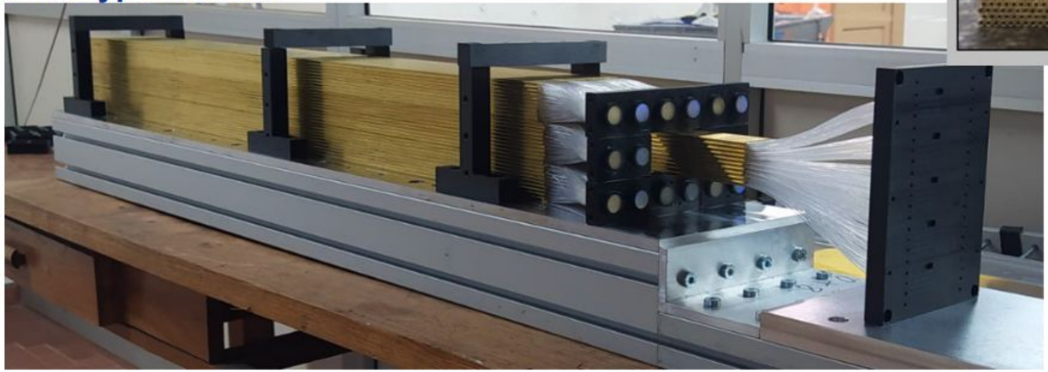
- Prototype based on **capillary brass tubes** of 2 mm outer diameter
  - Housing 1 mm diameter fibre
- Dimension to contain **EM shower** (10x10x100 cm^3) to 94% up to energies of 100 GeV
- 9 towers, each containing 16x20 capillary tubes (160 Cherenkov and 160 Scintillating fibres)
  - Laid out in **alternating rows** of S and C fibres
- M0 read out with **one SiPM per fibre**
- M1-8 **two PMTs each** (one for bundled C, one for bundled S)
- Two testbeams in 2021 at DESY & SPS (lead by European team)

Full prototype - 9 towers



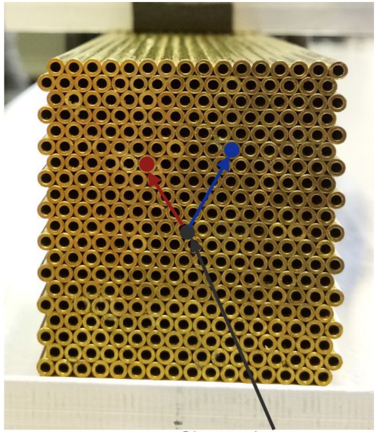
A single tower

Prototype rear end



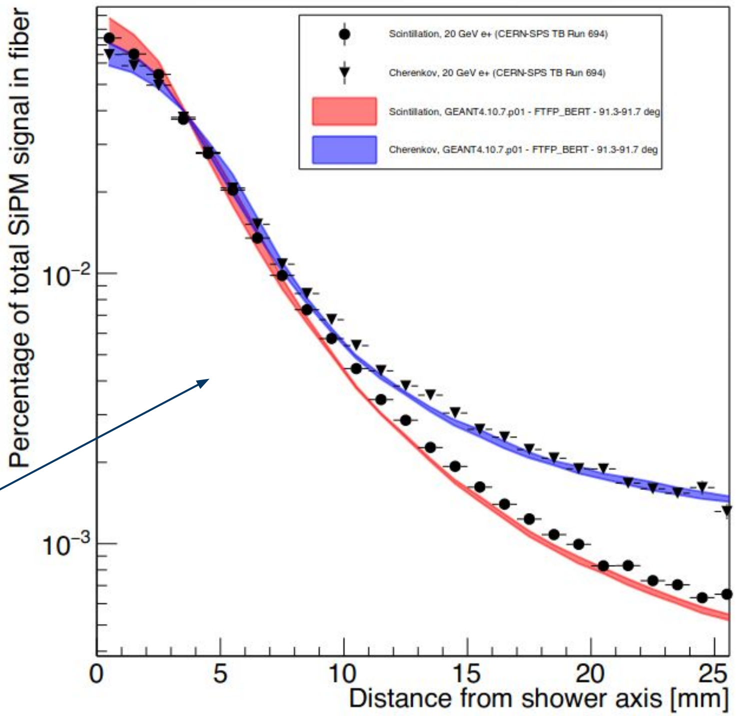
Lateral Shower Shape Measurement [resource]

- Need to confirm ability to reconstruct shower structure with testbeam prototype
- Lateral Profile: average signal carried by single fibre located at distance r from shower barycenter
- Compare testbeam results with simulation of prototype in Geant4



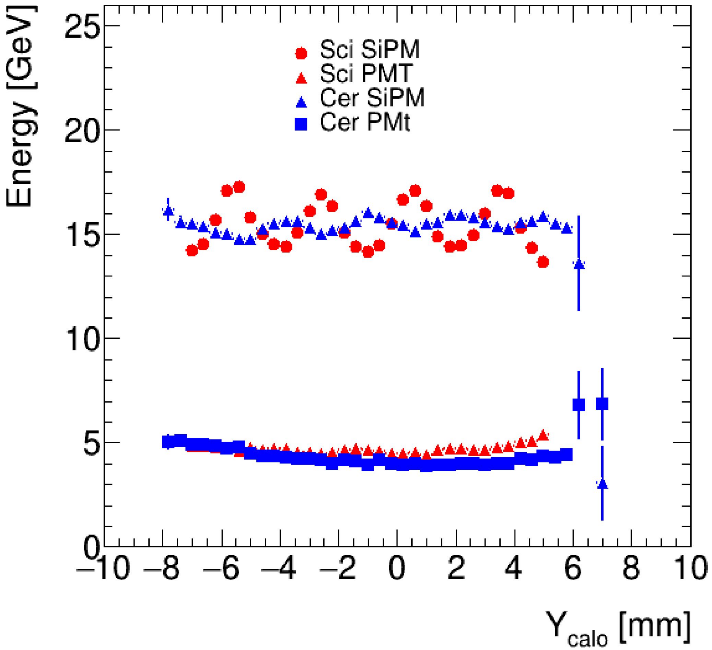
- **Good agreement with G4 simulation**
- **Shower barycenter reconstruction to $\mathcal{O}$(mm) possible**

CERN SPS 20 GeV e^+ - GEANT4 (log scale)

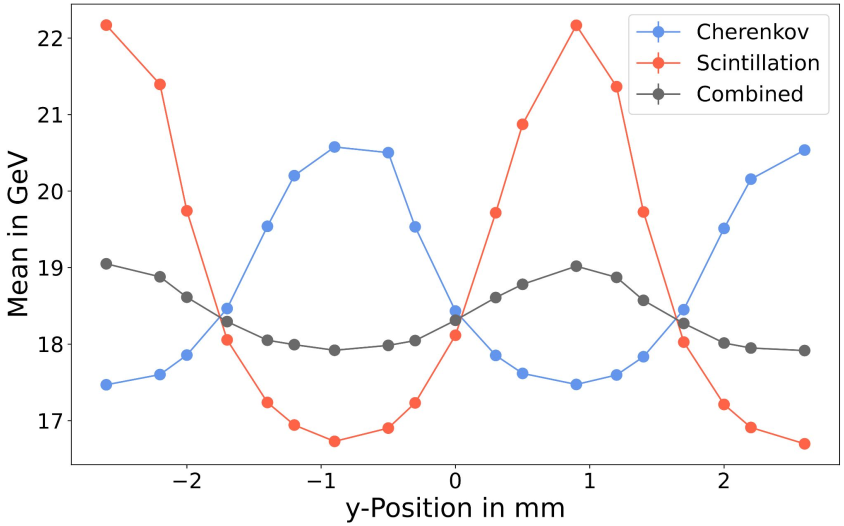


Energy Resolution (Preliminary) [resource]

- Problem: periodic structure in *y* leads to **oscillation** in both **S** and **C** channel with opposite phase
- Different amplitudes due to more collimated shower development in scintillating part of shower
  - Combining channel information **only partly cancels oscillating behaviour**
- Oscillation reproduced in simulation

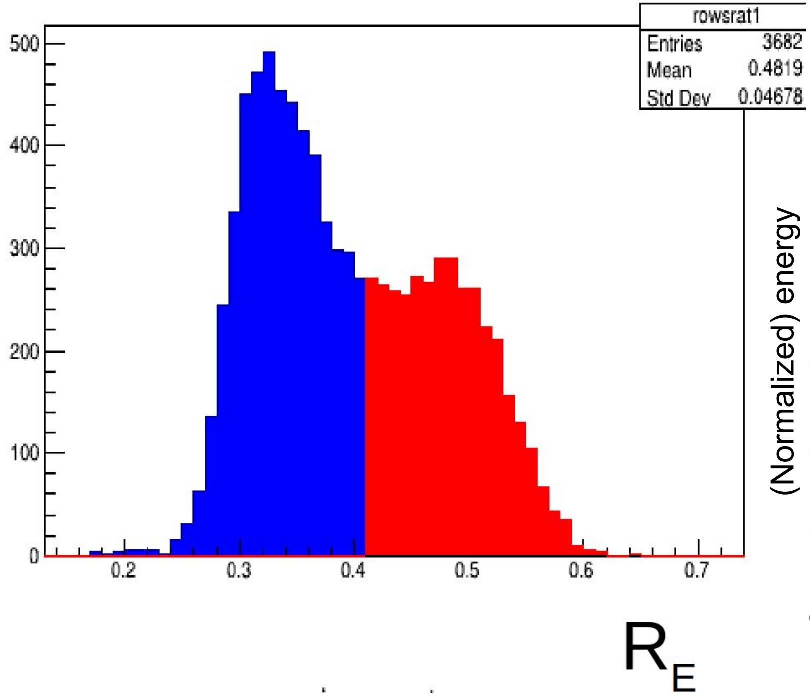


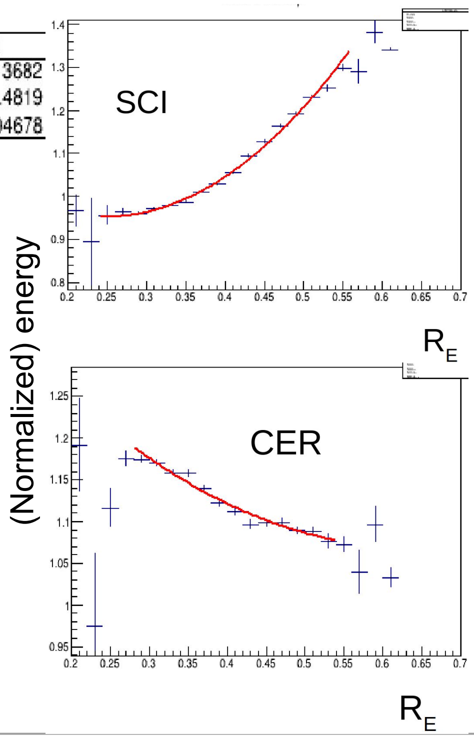
[resource]

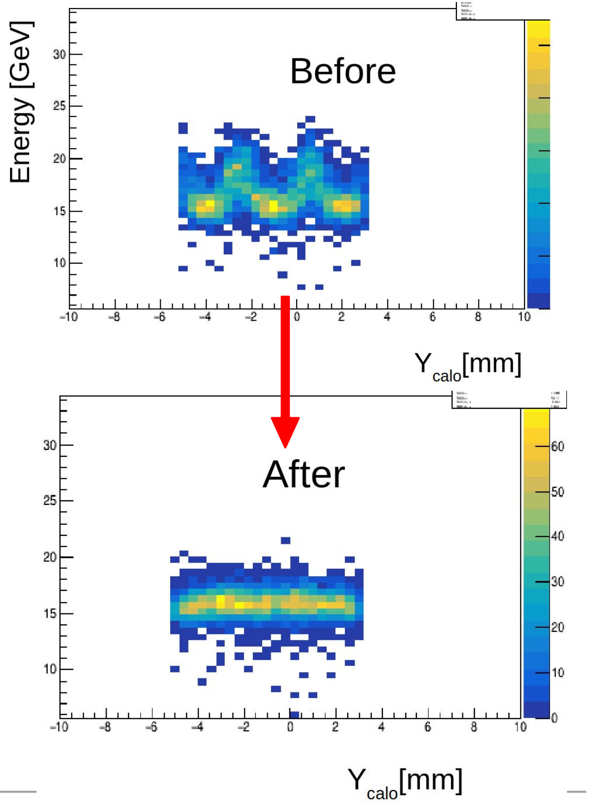


Energy Resolution (Preliminary) [resource]

- Separate regions based on ratio of 'hottest' scintillator row to total scintillator energy: $E^{row}_{max}/E_{tot} = R_E$
  - Region separation alone does not yield satisfactory energy resolution
  - Need to correct dependence of energy deposit on R_E

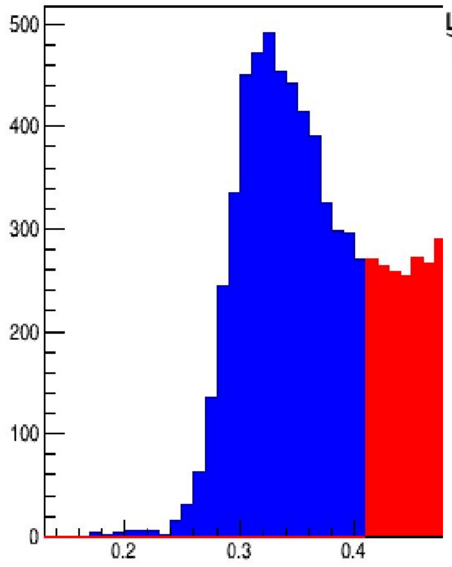


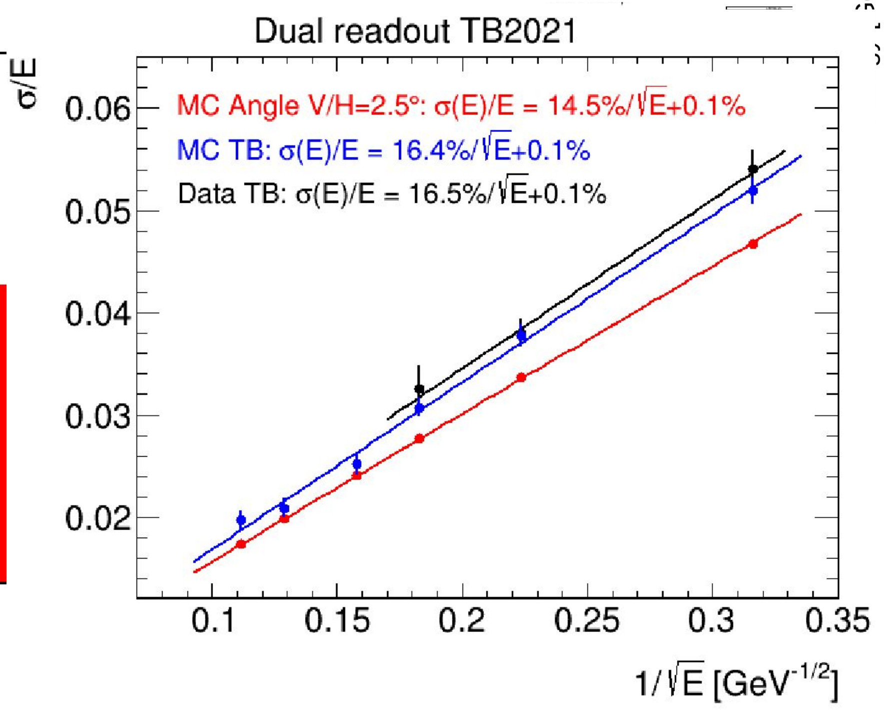


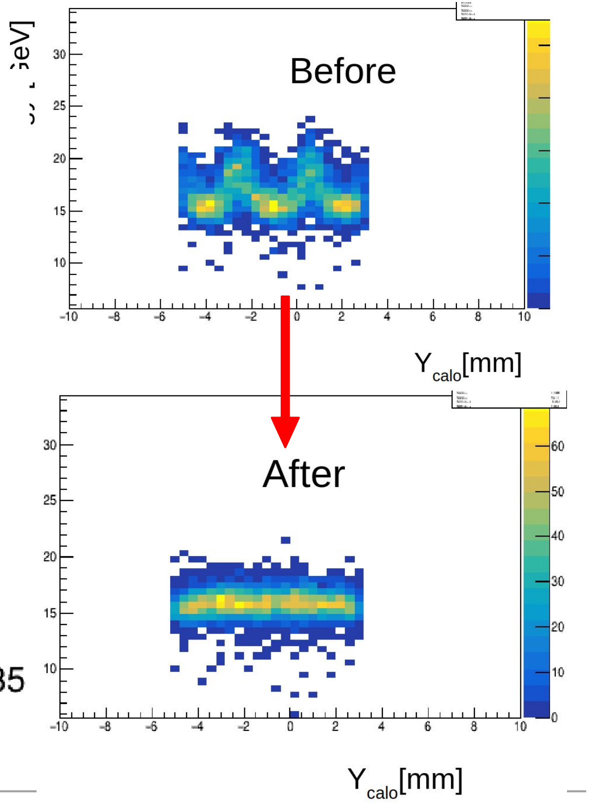


Energy Resolution (Preliminary) [resource]

- Separate regions based on ratio of 'hottest' scintillator row to total scintillator energy: $E^{row}_{max}/E_{tot} = R_E$
  - Region separation alone does not yield satisfactory energy resolution
  - Need to correct dependence of normalised energy deposition on R_E

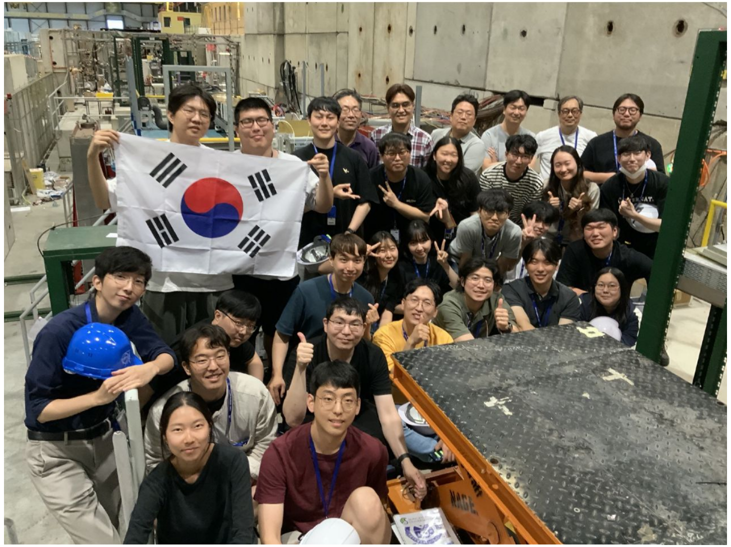


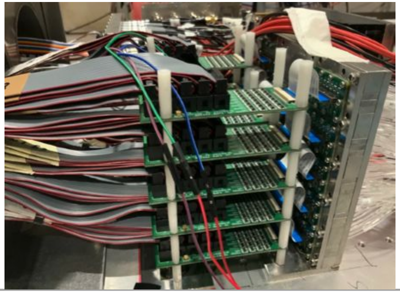


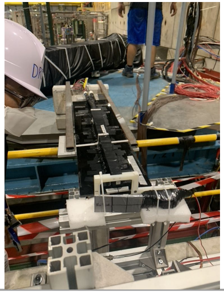


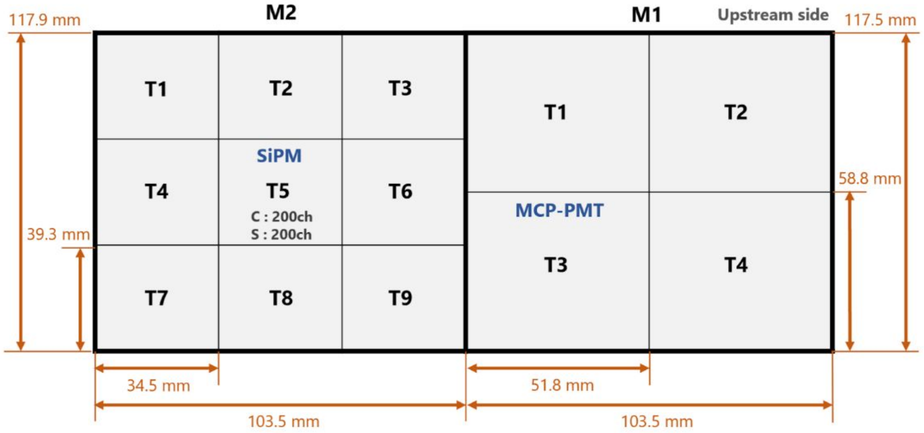
2022 Testbeam [resource]

- 2022 testbeam at SPS (lead by Korean team)
- Testing different mechanical construction options including a 3D printed module, different light sensors (SiPM, MCP-PMT), four types of optical fibres
- 84h of data taking, ~ 23M events in fast mode, 4.6M waveform mode
- Results to come soon



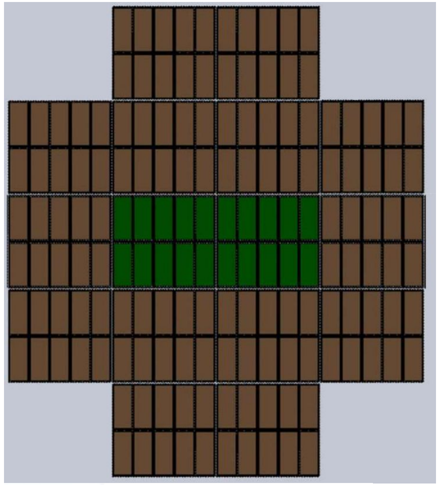






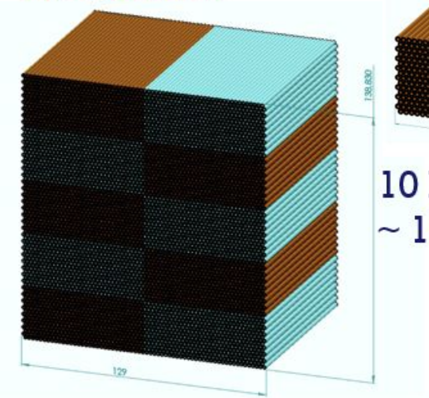
Preparation for Future TBs [resource]

- HiDra(2): High-Resolution Highly Granular Dual-Readout Demonstrator
- Larger size for hadronic containment needed to demonstrate hadronic resolution

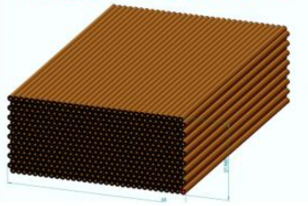


- ❑ 16 modules in total
- ❑ 2 central modules equipped with SiPMs
- ❑ 14 modules equipped with PMTs
- ❑ ~ 65 x 65 x 250 cm^3

The Module



The Mini-Module



10 Mini-modules
~ 13 x 13 x 250 cm^3

32 x 16 capillaries

2 readout options under discussion:

- Full granularity: 1 SiPM per channel (8 FERS required)
- Grouping: we sum the signals from 8 SiPMs (1 FERS required)

- 10k SiPMs for two central modules
- 140 PMTs for remaining 14 modules
- In process of identifying baseline options (absorber, fibres, and PMTs)

Summary

- **IDEA** detector concept implements a **fibre dual-readout calorimeter** as default option
  - Excellent hadronic energy resolution
  - **Lateral** shower shape measurement **$\mathcal{O}$(mm)**
  - Proof of concept for **longitudinal** shower shape sensitivity through timing
  - Good EM energy resolution (Simulation: **14%/√*E*** ; Testbeam: **16.5%/√*E***)
    - Option for **crystal, dual-readout ECAL**
- Two testbeam campaigns for EM-size **capillary tube (Bucatini)** prototype in 2021
  - Studies of TB data still ongoing
- Two copper plate modules + **3D-printed module** + full extraction of SiPM signal tested on beam in 2022
- The international effort for Dual-Readout Calorimetry at e^+e^- colliders is growing
- Plenty of room for further ideas and collaboration:
  - If you are interested: Subscribe on egroups.cern.ch to idea-dualreadout@cern.ch

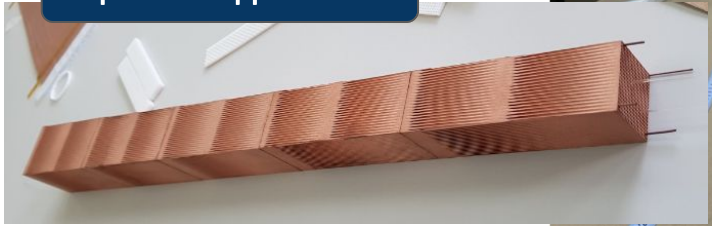
Thank you for your attention!

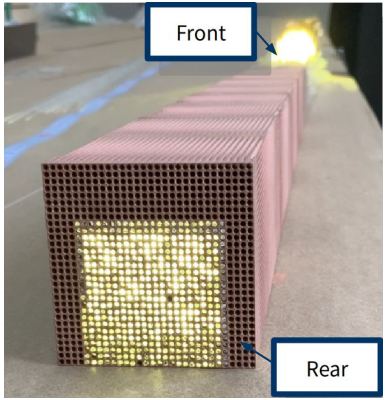
Backup-Slides

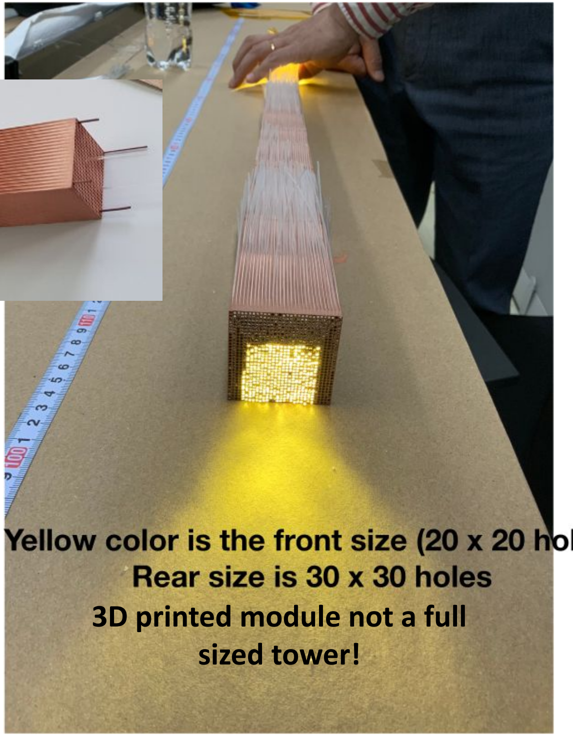
Tower Geometry

- Projective geometry with a uniform sampling fraction
  - more fibres in the rear than in the front

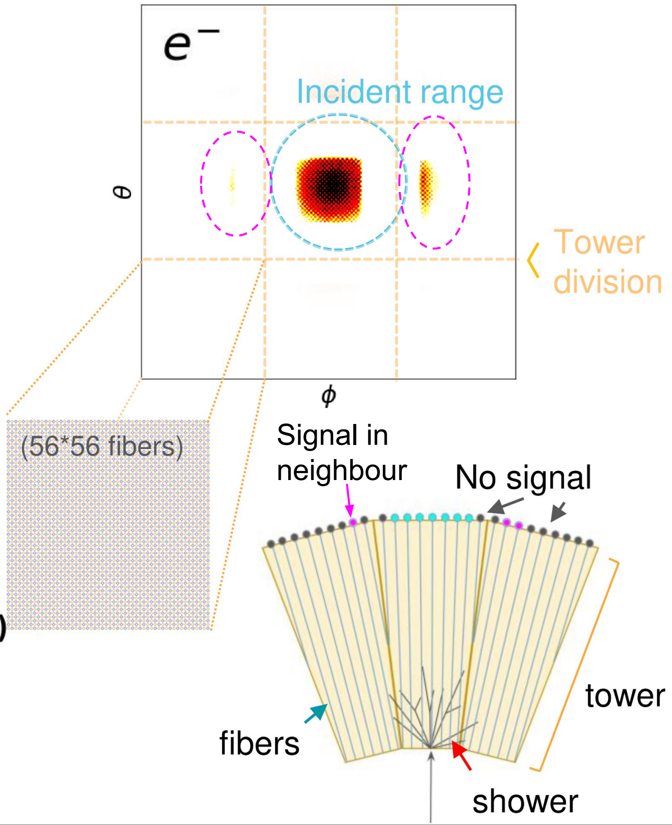
3D printed copper module



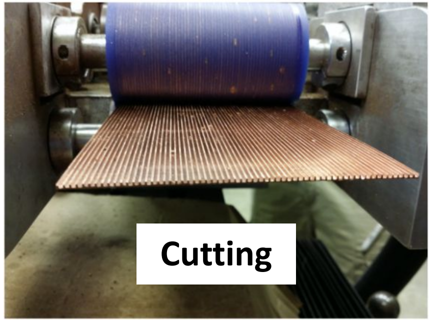


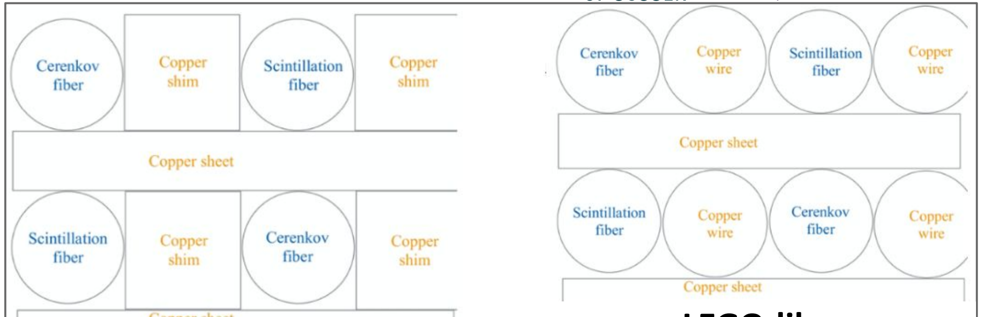


Average electron shower image



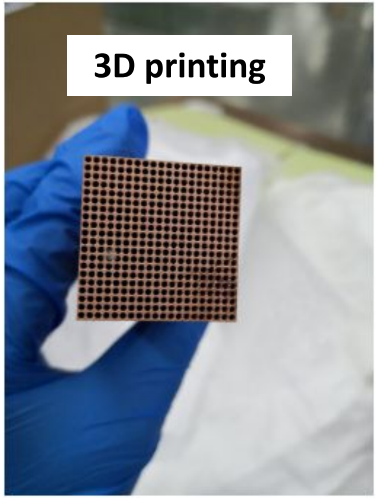
Construction Methods





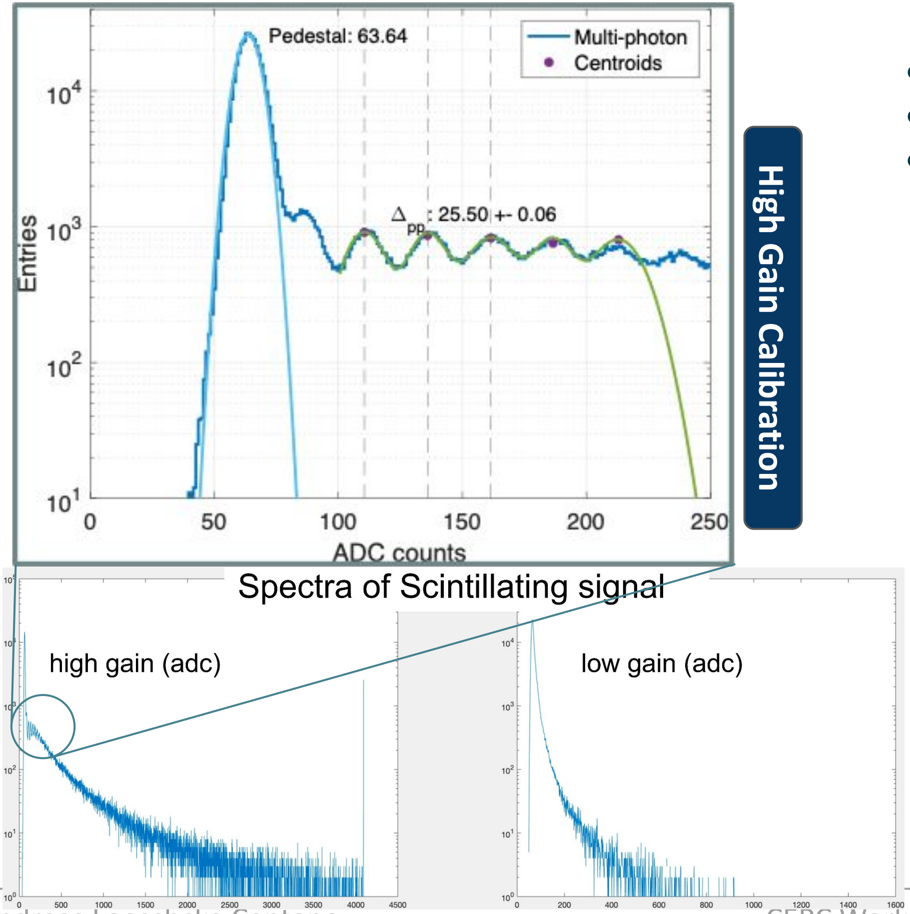
LEGO-like

	Cost	Preparation	Assembly	Accuracy	Performance
Cutting	Low	Difficult	Difficult	Fair	
Bucatini	Moderate (?)	(Semi-)Difficult	Easy	Excellent	Next step
3D printing (Preliminary)	Ultra high	Easiest	Easiest	Perfect	
LEGO-like	Very low	Very easy	Easy	Good	

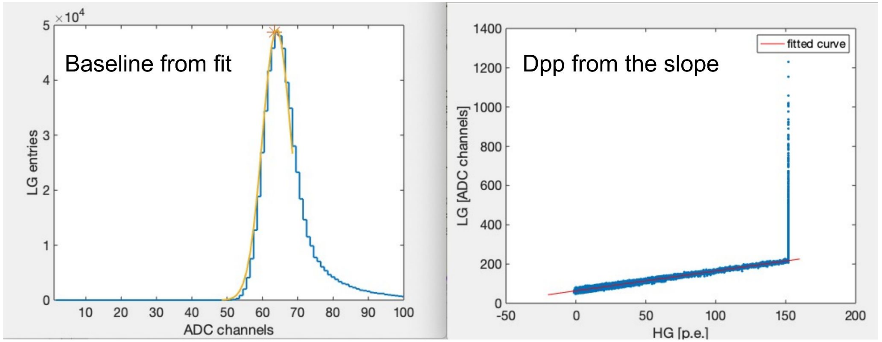


SiPM Calibration Procedure [resource]

- Each SiPM acquires low gain and high gain ADC values
- SiPM equalisation through multiphoton spectrum from high gain
- Intercalibration between high gain and low gain spectrum

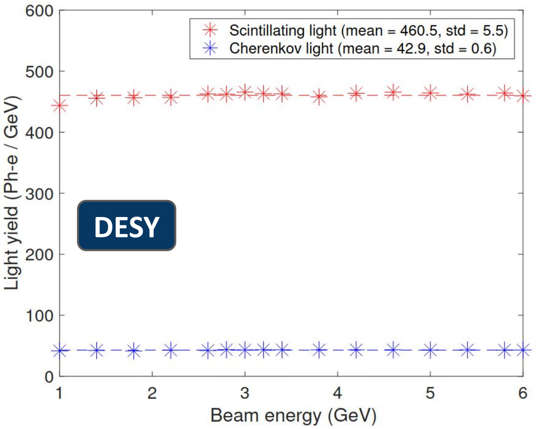


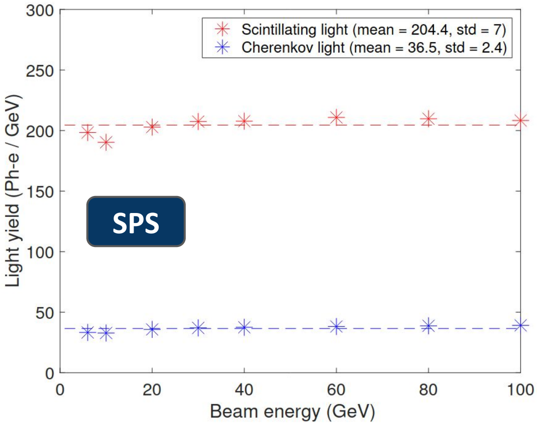
Low Gain Calibration

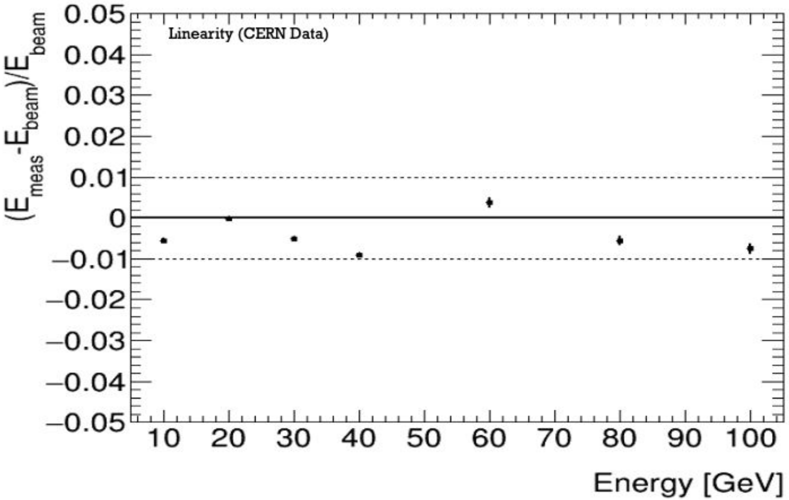


SiPM Calibration Procedure [resource]

Stable SiPM response at both testbeams (SPS & DESY)
- **no containment correction**
- **Difference for scintillation channel due to use of yellow filters**



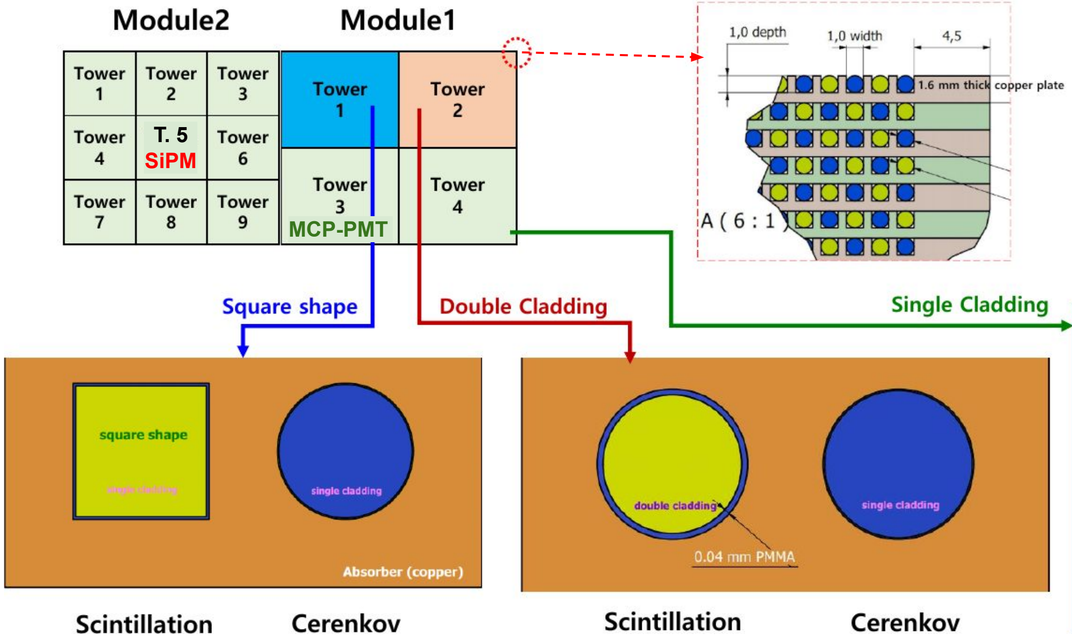


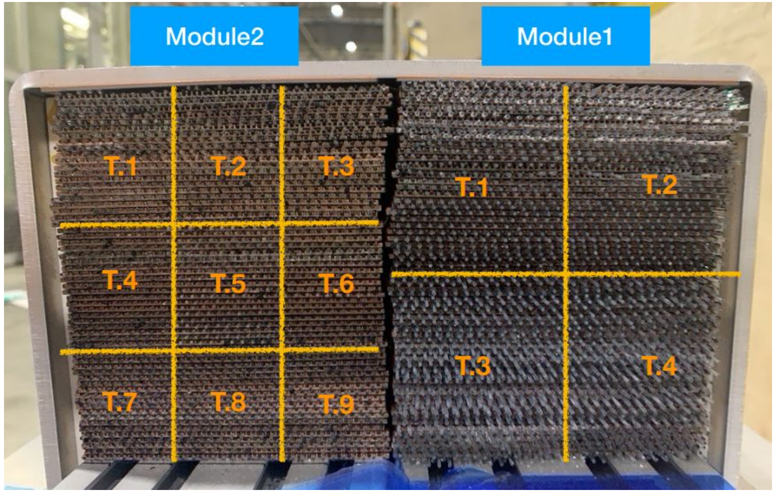


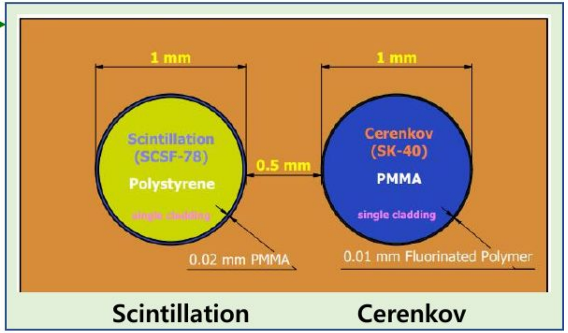
After calibration with electrons, linearity within 1% over wide range of energies (includes energy from PMTs)

2022 Testbeam [resource]

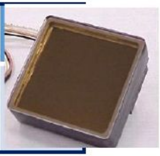
Module volume ~100x100x2500 mm^3







MCP-PMT	Window size	light	Quantum Efficiency (Q.E.)	max. HV (V)	Rise time (ns)
PLANACON XP85012	53x53 mm^2	scintillation	~7% at 550 nm	2400	0.6
PLANACON XP85112		Cerenkov	~21% at 400 nm	2800	0.5



SiPM	Photo-sensitive area	pixel size	photo detection efficiency (PDE)		number of pixels
S14160-1310PS	1.3x1.3 (1.69 mm^2)	10 µm	~15% at 400 nm	~17% at 550 nm	16675